

## Field

[0001] Embodiments of the present invention relate to memory circuits, and more particularly, to caches.

## Background

[0002] A cache is high-speed memory. To achieve high-speed performance, caches often employ dynamic (domino) logic. A high-level abstraction of a dynamic cache is provided in Fig. 1. The cache in Fig. 1 is addressable memory, where an address is provided on ports **102** to access one or more bits of information associated with the address. The cache shown in Fig. 1 may be part of a larger memory system, such as for example a content addressable memory system, where the address on ports **102** is obtained after tag matching.

[0003] The address on ports **102** is decoded by decoder **104**. In the particular example of Fig. 1, the address on ports **102** is 8 bits wide, so that decoder **104** is an 8-to-**256** bit decoder. There are **256** ports, labeled ports **106**. One of ports **106** is asserted HIGH, and the other remaining ports **106** are LOW, corresponding to the decoded 8 bit address at ports **102**. The signals on ports **106** are static in the sense that any port belonging to the set of ports **106** is held at a constant logical value (either HIGH or LOW) while an address is provided on port **102**.

[0004] Domino gate **108** provides dynamic (domino) compatible signals at its output ports **110**, indicative of the static signals on ports **106**. The signals on ports **110** are read-select signals, where a HIGH logical value indicates a read operation. Domino gate **108** is clocked by a clock signal, denoted by  $\phi$ , where  $\phi$  is HIGH during an evaluation phase and is LOW during a pre-charge phase. Domino gate **108** may comprise simple dynamic buffers, such as two dynamic inverters in series for each input/output port pair, so that the output signals on output ports **110** are LOW during a pre-charge phase, and take on the same logical values as the corresponding input signals on input ports **106** during an evaluation phase.

[0005] Set of memory cells **112** represents a set of memory cells, each memory cell sharing local bit line **114**. In the particular example of Fig. 1, set of memory cells **112** comprises 16 memory cells. Local bit line **114** is pulled HIGH by pullup pMOSFET **116** during a pre-charge phase, and a half-keeper comprising pMOSFET **118** and inverter **120**

keeps bit line **114** HIGH during an evaluation phase unless it is otherwise pulled LOW by one of the memory cells in set of memory cells **112**. For simplicity, only one set of memory cells with the corresponding local bit line are shown. For example, for the dynamic cache shown in Fig. 1, there will be 16 such sets of memory cells and local bit lines, each set of memory cells comprising 16 memory cells, for a total plurality of **256** memory cells.

[0006] Note that the roles of HIGH and LOW may be interchanged in the previous description regarding decoder **104**. That is, one of ports **106** may be asserted LOW, where the other remaining ports are HIGH. In that case, domino gate **108** need only comprise one inverter for each input/output port pair, so that a read-select signal on one of ports **110** is HIGH for a read operation.

[0007] An example of a set of memory cells sharing the same local bit line is provided in Fig. 2. For simplicity, Fig. 2 shows only that portion of a set of memory cells relevant to the present description. The gates of read-access transistors **202** are connected to the appropriate read-select ports **110** so as to receive the appropriate read-select signals. A typical memory cell **204** comprises cross-coupled inverters and a read-pass nMOSFET **210**. Not shown are the ports required for writing data into a memory cell. Note that in Fig. 1, clock signal  $\phi$  is buffered by inverters **122** before being applied to the gate of pullup pMOSFET **116** to account for the delay due to domino gate **108**. For simplicity, such inverters are omitted in Fig. 2, it being understood that a delay functional unit of some type may be needed in an actual circuit realization. Static unit **206** represents generic static logic, which may be inserted between domino circuit blocks of a larger circuit system, so that port **208** may be connected to other domino circuit blocks.

[0008] As device technology scales to smaller dimensions, sub-threshold leakage current may contribute to significant unwanted power dissipation in cache circuits, and may contribute to inaccurate readings of memory cells. For example, consider the case in which all memory cells in Fig. 2 are in a logical state such that the gates of read-pass transistors **210** are HIGH. During a pre-charge phase, bit line **114** will be charged HIGH and all read-access transistors **202** will be OFF. Nevertheless, the additive effect of sub-threshold leakage current in all read-access transistors **202** may cause significant current

flow from bit line **114** at the HIGH potential to ground at the LOW potential, thereby wasting power.

[0009] Furthermore, consider another case in which all memory cells in Fig. 2 are in a logical state such that the gates of all read-pass transistors **210** are LOW. If during an evaluation phase a read operation is performed on one of the memory cells, the sub-threshold leakage current in the read-pass transistor in the memory cell being read may cause bit line **114** to discharge to a sufficiently low potential such that an incorrect read operation occurs.

### **Brief Description of the Drawings**

- [0010] Fig. 1 is a prior art cache.  
[0011] Fig. 2 illustrates a portion of the prior art cache of Fig. 1.  
[0012] Fig. 3 is an embodiment according to the present invention.  
[0013] Fig. 4 illustrates a memory group belonging to the embodiment of Fig. 3.  
[0014] Fig. 5 is another embodiment of the present invention utilizing multiple foot transistors for each memory group.  
[0015] Fig. 6 illustrates a memory group belonging to the embodiment of Fig. 5.

### **Description of Embodiments**

[0016] An embodiment of the present invention is abstracted in Fig. 3. An  $n$ -bit address is provided at port **302**, where  $m$  most significant bits are provided to decoder **304**. Decoder **304** provides static signals at output ports **306**, representing the decoding of the  $m$  bits provided at input ports **308**. There are  $2^m$  ports in the plurality of output ports **306**. After being delayed by delay unit **310**, the  $2^m$  static signals representing the decoding of the  $m$  most significant address bits are used to drive the gates of the pullup pMOSFETs coupled to the local bit lines, one static signal for each pullup pMOSFET. These signals are referred to as local bit line select (lbl\_sel) signals, and their respective ports are referred to as local bit line select ports. In the example of Fig. 3, local bit line select port **316** is connected to the gate of pullup pMOSFET **318**. Local bit line select port **316** is also connected to the gate of foot transistor **320**. The function of foot transistor **320** will be described in more detail later. In the embodiment of Fig. 3, there are pluralities of  $2^m$  local bit lines,  $2^m$  pullup pMOSFETs, and  $2^m$  foot transistors.

[0017] The lower (least significant)  $(n - m)$  bits of the  $n$ -bit address are provided to post-decoder 324, and the output of decoder 304 is also provided to post-decoder 324, so that the signals on output ports 326 decode the entire  $n$ -bit address. In another embodiment, the entire  $n$ -bit address is provided to a decoder to provide the signals on ports 326. However, a savings in circuit area may be realized by the using a post-decoder as indicated in Fig. 3. There are  $2^n$  ports in the plurality of output ports 326.

[0018] The static signals from post-decoder 324 (or a full decoder if so used) are provided to domino gate 328 so as to be converted into dynamic (domino) read-select signals. Delay unit 310 is introduced to synchronize the local bit line select signals with the dynamic read-select signals. The plurality of  $2^n$  output ports (read-select ports 340) of domino gate 328 are grouped into  $2^m$  sets of read-select ports, each set having  $2^{n-m}$  read-select ports. There are  $2^m$  sets of memory cells, one for each set of read-select ports. Each set of memory cells has  $2^{n-m}$  memory cells, one for each read-select port in the corresponding set of read-select ports. There is a plurality of  $2^n$  memory cells. In the example of Fig. 3, one of the  $2^m$  sets of read-select ports 340 is coupled to set of memory cells 322 so as to implement a read operations on set of memory cells 322.

[0019] The  $2^m$  local bit lines,  $2^m$  pullup pMOSFETs,  $2^m$  foot transistors, and  $2^m$  sets of memory cells may be considered as belonging to groups, where a group has one set of memory cells, one foot transistor, one pullup pMOSFET, and one local bit line. A group comprises other components, such as a half-keeper connected to the group's local bit line. Such groups will be referred to as memory groups. The components belonging to a memory group are coupled together as indicated in Fig. 3. There clearly are  $2^m$  memory groups for the embodiment of Fig. 3.

[0020] The particular memory group comprising set of memory cells 322, pullup pMOSFET 318, foot transistor 320, and local bit line 114 is shown in Fig. 4. For simplicity, write ports and other features extraneous to understanding the present embodiments are not explicitly shown. As seen in Fig. 4, set of memory cells 322 of Fig. 3 includes individual memory cells 404, where read-access transistors 406 are coupled to read-select ports. During a pre-charge phase, the gates of read-access transistors 406 are

held LOW. During an evaluation phase, one of the gates of read-access transistors **406** may be brought HIGH if the corresponding memory cell is to be read.

**[0021]** Referring to Fig. 4, local bit line select port **316** is held HIGH if one of memory cells **404** is to be read, otherwise, it is held LOW. More generally stated, for each memory group, the local bit line select port coupled to a memory group is held HIGH if one of the memory cells in that memory group is to be read, otherwise, the local bit line select port is held LOW. Because there are  $2^m$  sets of read-select ports, a one-to-one correspondence may be made between the  $2^m$  local bit line select ports and the  $2^m$  sets of read-select ports such that a local bit line select port is HIGH if and only if a read-select port in the corresponding set of read-select ports is HIGH during an evaluation phase.

**[0022]** If a memory cell belonging to a memory group is to be read, then the corresponding local bit line select port is HIGH, so that the corresponding pullup pMOSFET is OFF and the corresponding foot transistor is ON. In this way, the memory group's local bit line will be discharged LOW if the memory cell to be read stores a logical state such that the gate of the corresponding read-pass transistor is HIGH (e.g., nMOSFET **410a** is the read-pass transistor for memory cell **404a**), otherwise, the half-keeper connected to the memory group's local bit line will maintain the local bit line in a charged HIGH state.

**[0023]** If, however, none of the memory cells in a memory group are to be read, then the corresponding local bit line select port is LOW, so that the corresponding pullup pMOSFET is ON and the corresponding foot transistor is OFF. The pullup pMOSFET keeps the local bit line held HIGH. With the foot transistor OFF, sub-threshold leakage current is reduced by the stack effect.

**[0024]** For example, consider the case in which none of the memory cells in Fig. 4 are to be read. Then the local bit line select port **316** is LOW, and consequently pullup pMOSFET **318** is ON and foot transistor **320** is OFF. Suppose memory cell **404a** stores a logical state such that the voltage potential of the gate of read-pass transistor **410a** is LOW. If sub-threshold current were to flow through nMOSFET **410a** and to ground via foot transistor **320**, then the voltage potential of the drain of foot transistor **316** would rise above the ground potential (LOW). Consequently, with the drain of foot transistor **316**

connected to the source of read-pass transistor **410a**, this would cause the voltage potential of the source of read-pass transistor **410a** to rise above LOW, and read-pass transistor **410a** would be reverse biased because its gate-to-source voltage difference would be negative. Read-pass transistor **410a** is thus strongly turned OFF, resulting in a significant reduction in sub-threshold leakage current. This effect of reducing sub-threshold leakage current by connecting two nMOSFETs in series, where the gates are LOW, is known as the stack effect.

[0025] Continuing with the above example, suppose the logical state of memory cell **404a** is such that the voltage potential of the gate of read-pass transistor **410a** is HIGH. The voltage potential of the gate of read-access transistor **406a** is LOW because it has been assumed in this particular case that none of the memory cells are to be read, that is, all read-select signals provided to the memory group are LOW. Then, read-access transistor **406a** together with foot transistor **320** realize the stack effect, so that sub-threshold leakage current is again significantly reduced.

[0026] It is seen that when no read operation is being performed on a memory cell, either the combination of the corresponding foot transistor and read-access transistor, or the combination of the corresponding foot transistor and read-pass transistor, realize a stack effect. Consequently, the use of a foot transistor in a memory group reduces sub-threshold leakage current due to the stack effect, regardless of the stored state of the memory cell, provided a read operation is not performed.

[0027] After a memory cell is read, the corresponding local bit line may be discharged LOW, depending upon the logical state of the memory cell. Consequently, after a read operation is performed during an evaluation phase, in the immediately following pre-charge phase the corresponding local bit line should be charged HIGH if it had been discharged LOW so that a subsequent read operation during the next evaluation phase to the same or other memory cell within the corresponding memory group will provide the correct result. This may be accomplished by gating delay unit **310** by the clock signal  $\phi$  as indicated in Fig. 3, so that during a pre-charge phase when  $\phi$  is LOW, the local bit line select ports are LOW. This gating may be performed in another part of the signal path, such as decoder **304**.

**[0028]** Another embodiment is abstracted in Fig. 5, where components in Fig. 5 operate in the same fashion as correspondingly labeled components in Fig. 3. As before, the  $m$  most significant bits of the  $n$ -bit address are decoded into  $2^m$  local bit line select signals, and the entire  $n$ -bit address is decoded into  $2^n$  read-select signals grouped into  $2^m$  sets where each set has  $2^{n-m}$  read-select signals. Also, as before, there are  $2^m$  memory groups where each memory group has  $2^{n-m}$  memory cells connected to the  $2^{n-m}$  read-select ports of one of the  $2^m$  sets of read-select ports **340**, and there is a one-to-one correspondence between the  $2^m$  local bit line ports and the  $2^m$  sets of read-select ports such that a local bit line select port is HIGH if and only if a read-select port in the corresponding set of read-select ports is HIGH. However, note that for the embodiment of Fig. 5, the local bit line select ports do not connect directly to the foot transistors.

**[0029]** Post-decoder **502**, in addition to effectively decoding all  $n$  bits of the  $n$ -bit address, also decodes the  $m+k$  most significant bits of the  $n$ -bit address, where  $m+k \leq n$ , to provide  $2^{m+k}$  signals on  $2^{m+k}$  ports **506**, referred to respectively as foot transistor select (ft\_sel) signals and foot transistor select ports. These  $2^{m+k}$  foot transistor select ports are grouped into  $2^m$  sets of foot transistor select ports, each set having  $2^k$  foot transistor select ports. There is a one-to-one correspondence between the  $2^m$  local bit line select ports and the  $2^m$  sets of foot transistor select ports, where a local bit line select port is HIGH if and only if a foot transistor select port in the corresponding subset of foot transistor select ports is HIGH.

**[0030]** Consequently, corresponding to every memory group is a local bit line select port, a set of read-select ports, and a set of foot transistor select ports. If the local bit line select port to a memory group is HIGH, then during an evaluation phase there is one foot transistor select port to the memory group that is HIGH and one read-select port to the memory group that is HIGH. If the local bit line select port to a memory group is LOW, then during an evaluation phase all foot transistor select ports to the memory group are LOW and all read-select ports to the memory group are LOW.

**[0031]** Each memory group has  $2^k$  foot transistors, where the gate of each foot transistor in a memory group is connected to one of the  $2^k$  foot transistor select ports in the corresponding set of foot transistor ports. For each memory group, the set of memory

cells are grouped into  $2^k$  subsets of memory cells, where each subset of memory cells is connected to one of the  $2^k$  foot transistors. Each subset of memory cells has  $2^{n-m-k}$  memory cells. Accordingly, the  $2^{n-m}$  read-select ports corresponding to each memory group may be viewed as grouped into  $2^k$  subsets, each subset having  $2^{n-m-k}$  read-select ports, where each subset of read-select ports is in one-to-one correspondence with each subset of memory cells. Furthermore, the read-select ports and foot transistors are connected to the memory cells such that if all the memory cells in a subset of memory cells are not to be read, then the corresponding foot transistor is OFF, and if one of the memory cells in a subset of memory cells is to be read, then the corresponding foot transistor is ON.

[0032] Note that there are  $2^{m+k}$  foot transistors for the embodiment of Fig. 5, whereas there are  $2^m$  foot transistors for the embodiment of Fig. 3. The number local bit lines, pullup transistors, memory cells in the two embodiments are the same for equal  $n$  and  $m$ . The embodiment of Fig. 5 essentially reduces to that of Fig. 4 for the special case in which  $k = 0$ .

[0033] The memory group in Fig. 5 comprising set of memory cells 322, pullup pMOSFET 318, and foot transistors 504 is shown in Fig. 6, where for simplicity the half-keeper and write ports are not shown. The operation of the memory group in Fig. 6 is similar to that of Fig. 4, and many of the details need not be repeated. However, because there are now only  $2^{n-m-k}$  memory cells connected to any one foot transistor, the cache of Fig. 5 should be more robust than that of Fig. 3 for the same size  $n$  and  $m$ . This is seen by observing that during a read operation in a memory group, only one of the foot transistors in the memory group is ON, the others being OFF. For those memory cells connected to the OFF foot transistors, the stack effect significantly reduces sub-threshold leakage current. For the memory cells connected to the ON foot transistor, the stack effect is not present. But there are now only  $2^{n-m-k}$  memory cells connected to the ON foot transistor. Consequently, if the memory cell to be read has a stored logical state such that the corresponding read-pass transistor is OFF, then with only  $2^{n-m-k}$  memory cells connected to the ON foot transistor, there is less sub-threshold leakage current than for the structure



of Fig. 4 (for the same process technology and transistor size), and consequently the local bit line is less likely to discharge LOW and provide an incorrect read.

**[0034]** Various modifications may be made to the disclosed embodiments without departing from the scope of the invention as claimed below. For example, the pullup pMOSFETs for the local bit lines may be clocked as in Fig. 1 instead of driven by the local bit line select signals, where the foot transistors are still controlled by the local bit line select signals as in Fig. 3 or the foot transistor select signals as in Fig. 5. However, using static signals to drive the pullup pMOSFETs may be advantageous in that the clocking distribution network is reduced, thereby leading to a savings in power dissipation. Furthermore, embodiments using static signals to maintain the local bit lines in their charged states may be more robust than using dynamic signals where a half-keeper maintains the local bit lines HIGH during the evaluation phases (unless one is pulled LOW during a read operation).

**[0035]** Furthermore, other embodiments may be realized in which the various subsets of memory cells within a memory group need not be the same size. Also, it is not necessary that the various described sets and subsets be powers of two. Furthermore, it is not necessary that the memory groups be of the same size. However, embodiments in which the various sets and subsets are powers of two, and for which each memory group is of the same size and each subset of memory cells within a memory group is of the same size, may be easier to implement than other embodiments.

**[0036]** It is immaterial to the claimed scope of the invention as to how the various decoders and or post-decoders are implemented, and whether post-decoders are utilized at all. For example, in Fig. 5, two decoders may be substituted for post-decoder **502** (the feedback from decoder **304** to post-decoder **502** is eliminated), where one decoder decodes the entire  $n$ -bit address to provide the  $2^n$  read-select signals, and the other decoder decodes the least significant  $n - m$  bits of the  $n$ -bit address to provide the  $2^{m+k}$  foot transistor select signals. Consequently, it is to be understood that the term "decoder" encompasses not just a single decoder, but perhaps one or more decoders, and perhaps one or more post-decoders, where the various decoders and post-decoders decode various bits of an address. It is also to be understood that a set of objects, such as a set of memory

cells, may contain only one such object. A similar statement also applies to a subset of objects.

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